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TRANSPORTATION POLICY ANALYSIS WITH A GEOGRAPHIC INFORMATION SYSTEM: THE VIRTUAL NETWORK OF FREIGHT TRANSPORTATION IN EUROPE

Abstract: This paper presents a multimodal freight transportation model based on a digitized map of the European countries. The goal of this research is to estimate the impact of a cost variation of one of these transportation modes on the market shares of the all the considered modes. To achieve this objective, aggregated Eurostat O-D matrixes for the different transportation modes were used. In order to obtain a point-to-point O-D matrix, a distribution method based on a Monte-Carlo technique is implemented. This approach can be justified by the particular topology of the used map.

The O-D matrix is then assigned on the Virtual Network generated from the real map. The Virtual Network is a monomodal representation of a multimodal network. As cost functions were developed for the different operations, a particular trip assigned on the virtual network can combine different transportation modes.

Once the complete matrix assigned on the Virtual Network, the estimated modal is compared to the real one. After calibration, the costs linked to one particular transportation mode are stepwise modified. On each step, the O-D matrix is reassigned and the market shares of the different transportation modes are computed. A short economic discussion is proposed to explain the presented results.

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1 The authors are grateful to the « Services Fédéraux des Affaires Scientifiques, Techniques et Culturelles » (SSTC) for granting a financial support for this research.
Introduction

The computing facilities which are available nowadays, their speed and power as well as their programming ease, have lead to the development of Geographic Information Systems (G.I.S.) which can provide a number of services to geographers, urban planners, geologists, engineers, as well as to economists working in the fields of spatial analysis and transportation. Most of them have been developed by consultants or firms for rather specific purposes, but they are often not too well documented and include black boxes with programs and information which remain « confidential ».

For these reasons, the purpose of this paper is not to review the field of G.I.S. software applied to transportation, which would be a worthwhile but rather difficult task. We just wish to provide an exposé of a systematic G.I.S. analysis for freight transportation over long distances, as it has been recently developed for the trans-European network in the Mons Facultés (Jourquin, 1995). As it will be explained below, it has the advantage on other systems to be completely open and flexible: it can be used with external programs especially designed to solve particular problems. Moreover, its detailed analytical structure permits an easy set-up of all its parameters. It is also one of the very few G.I.S. focusing on transportation of goods2.

Based on a full decomposition of all transport operations over a multi-modal geographic network, i.e. loading, moving, unloading, transshipping and transiting, it creates an expanded virtual network which gives a mono-modal version of a complex multi-modal network. Different types of virtual links correspond to moving goods by different modes and by transportation means of different sizes or characteristics; some others correspond to the possibilities of transferring the goods from one mode or mean to another. Hence, the alternatives of combined transports can be taken into account. Specific generalized cost functions, in terms of distance, time and cost, can be attached to each virtual link. Then, given a transportation task, it is possible to minimize, for instance, its total cost by the choice of the best combination of mode, mean and route.

This model of analysis, with its associated software, constitutes a powerful tool for evaluating the impacts of transportation's new infrastructures and policies. Actually, that was the motivation behind its development, and it partly explains our emphasis on the costs of the means and modes of transportation. Obviously, savings in the costs of transports are one important benefit of new infrastructures; with this model, they can be easily computed in a comprehensive way over a complete national or trans-European network. We have already used it for that purpose in evaluations of some public investments in waterways (Beuthe and Jourquin 1994b). In the same spirit, we used it for estimating the additional cost of transportation resulting from the State controlled organization of inland waterways transports in Belgium (Beuthe and Jourquin, 1994a). Within the context of the European governmental discussions over the needed improvements of the trans-European network, we wish to examine in the present paper the relative competitive situations and market shares of the three inland transportation modes: railways, roads and waterways.

This paper will start with a presentation of the virtual network and its methods for defining the network links and generating automatically the full virtual network. A second section will discuss the cost functions which are attached to each link of this network, and the method of total cost minimization which is applied. The third section will present the trans-European

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2 The most interesting one is STAN by Crainic, Florian, Guélat, and Spiess (1990), which provided useful insights for the present research. We thank also T.G. Crainic for his many stimulating comments.
network and the market shares analysis. A short discussion of further possible developments will
be proposed as concluding comments.

1. The virtual network

Transportation of goods on a real network may be realized by various means on the same
infrastructure. For instance, the same large canal can be used by small and large boats. Transportation also involves many different operations which do not appear in a normal
geographic representation of the network, i.e. loading, moving, unloading, transshipping and
transiting. In particular, the operations of transferring goods from one mean or mode to another
are not represented. However, in order to properly analyze a transportation problem with all its
alternative solutions and operating dimensions, it is necessary to identify and separate each
transport operation. This can be achieved by creating a network, a virtual network, linking in a
systematic way all the possible successive operations in the geographic space.

In the context of freight transportation models, the idea of virtual links was initiated by Harker
(1987), who extended its general spatial price equilibrium model with additional links
corresponding to different levels of services. It was further developed by Crainic et alii (1990) in
order to define a multi-modal network with links connecting the various modes. Jourquin’s
recent contribution (1995) is to propose an automatic generation of all the virtual links on the
basis of a well structured notation of the real nodes and links. His method allows to deal rather
easily with very large networks like the trans-European one and facilitates greatly any ensuing
sensitivity analyses. It uses a particular structured notation that provides a convenient matching
of each specific link with the appropriate weight or cost functions.

This automatic generation starts with the tabulation of the real network $G=(X, U)$ which
enumerates the links $U_j$ of the graph of the real network, their associated end-nodes $X_i$ and $X_k$,
and the modes $t$ and means $m$ which can be used on the links. Then, virtual links are created
automatically for each possible mode and mean on each real link; they are defined by their two
virtual end-nodes $X_{ijtm}$ and $X_{kjtjm}$.

The next step is to create the virtual links corresponding to transshipping operations. That can
be done by a systematic comparison of the virtual nodes which could so be linked. Transshipping
operations are possible between all virtual nodes pertaining to a same real node, like a
transshipment between a ship and a truck. However, no transshipment should be possible
between these nodes when they relate to the same real link $j$, since that would be like a
transshipment between two means of the same mode before turning back on the same real link.

Besides these transshipping virtual links, it may be convenient to include transiting virtual links
for the simple passage from one virtual node to another without changing the mode or the mean
of transportation. These links will connect virtual nodes with same $i$, $t$ and $m$ but different $j$.

The last step deals with the operations of loading and unloading at the real nodes. This problem
is handled by the creation of virtual nodes $X_{ij000}$ for each real node $X_i$. It is then possible to
create a set of virtual links corresponding to these operations between $X_{ij000}$ and every virtual
node $X_{ijtm}$.

In some cases, this method of automatic and exhaustive generation of virtual nodes and links
may create virtual links corresponding to operations which cannot be proceeded at some nodes,
like the handling of containers in some places without adequate facilities. This problem is
handled by defining a list of exclusions for each real node, which is checked during the process of creating the virtual links and nodes.

Because of possible differences between loading and unloading costs for instance, the generated virtual network must be oriented. To that effect, separate arrows are created between the two end-nodes for each virtual link.

Now, it can be seen how this notation allows us to match easily the virtual links defined by a particular operation to the corresponding cost functions. Actually, the two end-nodes defining a link provide the necessary information:

- When two virtual end-nodes relate to different real nodes $i$ and $k$, the virtual link corresponds to a moving operation between $i$ and $k$, to which must be attached the relevant cost function for mode $t$ and mean $m$.
- When the nodes refer to different real links $j$ and $l$, but to the same mode $t$ and mean $m$, it is a simple transit operation, to which must be attached the relevant cost, if any.
- When the nodes refer to different real links and different modes $t$ and $t'$ and/or to different means $m$ and $m'$, it must be a transshipping operation, for which there is a special set of cost functions.
- When one of the nodes is $X_i^{000}$, it must be a loading or unloading operation, for which there are some other particular functions.

As an example, figure 1 presents a very simple real network which supports railways (R) and waterways (W). To illustrate the difference which exists between transportation modes and transportation means, link $U_1$ of this simple network represents a large canal (W2) that supports small (1) and large (2) boats. Figure 2 presents the corresponding virtual network at node $X_b$, where the operations of loading, unloading and transshipping are explicitly included.

![Figure 1: Simplified real network](image)
2. Cost functions and total cost minimization

2.1. General considerations on cost minimization

The main objective of this network model is to predict the choices of modes, means and routes which would result from the minimization of the total cost of transports for a given transportation task defined by a matrix of origins-destinations.

This total cost, which must minimized with respect to the choices of modes \((t)\), means \((m)\), and routes \((l)\), can be defined as \(\text{TC} = \sum_l \sum_t \sum_m \text{TC}_{ilm}\), where \(\text{TC}_{ilm}\) is the sub-total cost for the traffic on a particular route \(l\) with mode \(t\) and mean \(m\). \(\text{TC}_{ilm}\) is the sum of all the costs over the successive links (or operations) of the virtual network over route \(l\), and we suppose that all these costs are proportional to the total quantity transported \(Q_{ilm}\). This means that the minimization will result in a All or Nothing assignment procedure, such that all the traffic flow \(Q_{OD}\) of a particular origin-destination will be assigned to the same combination of mode, mean and route which minimizes the total cost of transporting one ton.

If we suppose also that all the costs per ton for a link \(j\) are either constant or proportional to the distance \(s_j\), we can write:

\[
\text{TC} = \sum_l \sum_t \sum_m Q_{ilm} \left( \sum_{j=1}^{A^m_{ij}} + \sum_{j=1}^{B^m_{ij}} s_j \right),
\]

where \(s_j\) is the distance over the link \(j\).

This is the total cost which must be minimized with respect to \(l, t,\) and \(m\). After attaching the relevant cost functions to all the links, this operation can be realized by applying the algorithms of Moore-Dijkstra (1959) or Johnson (1973) to the virtual network.

This general framework being defined, we can now have a closer look at the various cost functions which are used with the network: the vehicles related costs, the handling costs and the capital opportunity costs.
2.2. Vehicles related costs

For a given link, the vehicles' costs for transporting one ton over a distance $s$ by mode $t$ and mean $m$ are taken to be a linear function of distance $s$: $A^m + B^m s$.

The constant $A^m$ corresponds to the fixed costs incurred for the vehicles and the personnel working on the vehicle (the driver of the truck or the crew of the boat for instance) during the time taken for loading and unloading. They are based on capital annuities, insurance and (sometimes) maintenance costs, and on the wages of the personnel. But, because loading and unloading generally require different times, we have to distinguish $A_l^m$, the fixed cost during loading, and $A_u^m$, the fixed cost during unloading. There are also similar costs for transshipping goods from one mode or mean to another.

For estimating all these times, we use Deming's (1978) formula, whereby: handling-time = $a + b * \text{quantity}$, a non-linear relation between handling time and handled quantity. We use also the coefficients estimated by Deming for the three modes and the different operations.

The cost of moving one ton over a distance $s$ is proportional to that distance, as $B^m$, the cost per km, is a constant. $B^m$ takes into account the same factors as above, but is also function of the average speed, the fuel consumption when loaded or empty, and the average loading rate. Note that the real distance may be adjusted to take into account various delays which may be encountered on a link.

More details are given in the appendix on the specifications of these functions for the different modes and means relevant for the present application: boats, barges, diesel and electric powered trains and trucks.

2.3. Other handling costs

Besides these vehicles' costs, we have to take into account the labor costs of handling the goods at the points of origins and destination, or when the goods are transferred from one mode or mean to another. Their estimation is based on the same formula as above.

Also, there may be some other costs related to delays, administrative paperwork or even congestion at some points of the network. These additional costs can be easily included as additional constant costs. An additional link in the virtual network may even be introduced, in order to take them into account as costs of a particular operation, like the crossing of a national boundary for example. These are transit costs.

2.4. Inventory cost

It is the opportunity cost of the capital tied into the goods during transportation. It is proportional to the time taken by the transports, all operations included. Its importance varies with the rate of interest and the value of the goods.

2.5. The objective function

As explained in Section 2, the virtual network definition is founded on the decomposition of the transport activity into all its particular operations: loading, moving, transshipping, unloading,
and transiting. To each of these operations corresponds specific virtual links. Moreover, the numbers which identify two virtual end-nodes indicate clearly which operation is made on a particular link, so that it is easily possible to attach the appropriate cost functions to each virtual link. In this Section 3, we have discussed the specifications of the various cost functions introduced in the virtual network. This allows us to rewrite the total cost function which must be minimized in the following general way:

\[
TC = \sum_{\text{Origin-Destination}} \sum_{\text{Mode/ Mean Route}} \left[ \sum \text{costs} \right]
\]

3. Application to the Trans-European Network

3.1. The distribution of the global flows

We have applied the concepts and techniques described in the above sections to the trans-European transportation network of the twelve countries which were members of the European Union in 1991. The digitized geographic network is based on the 'Trunk Lines of Communication of International Importance' published by the European Conference of Ministers of Transport (ECMT). Data of global transport flows between these countries are provided by Eurostat for the different modes and categories of goods. In this paper, we have chosen to present the case of wood transports. However, the data available do not give any indication about specific points or regions of origins and destination.

In order to solve this problem, we have created a set of centroïds as additional nodes of the network. They can be defined as regional centers of gravity, which are taken as points of origins and destinations of the goods. In order to obtain these centroïds, each real node of the network was assigned to the closest harbor and, in a second step, to the closest railway station. A centroïd was created for each of these clusters of nodes, as a point of unique origin or destination. Moreover, a road link was also created between the centroïd and the nearest harbor or railway station. The distance assigned to that link was the average distance of the nodes in each cluster to the harbor or railway station.

Obviously, these centroïds are not evenly distributed over the network, but they are more numerous in industrialized areas where the density of the network is greater. To that extent, it is likely that their distribution over the geographic space corresponds to the distribution of the real origins and destinations. Thus, we assigned the total flows of goods among all the centroïds by

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3 Eurostat publishes all the statistics available on the European Union. No data are given for combined transports. Hence, we shall not identify these transports in this paper, but assign all transports to the mode which is mainly used on a route.

4 On the basis of prices published by OECD, the value of the transported wood per ton is 4,954 FB.
repeated random drawings of centroids for small bundles of goods. By this Monte Carlo procedure, we obtained a detailed O-D matrix which is probably very similar to the real one.

Given this O-D matrix and all the cost functions for the various operations, it is now possible to minimize the total cost of the transportation task by choosing the cheapest combinations of modes, means and routes. As explained above, this cost minimization is made on the basis of a All or Nothing procedure for each O-D pair, so that all the corresponding traffic flow is assigned to the same combination of transportation mode and mean on the same route. Obviously, this procedure supposes that there is no capacity constraint. This hypothesis can be accepted in the present context of an analysis of annual transport flows spread over a long period of time and a large network.

3.2. The impact of a cost variation on the modes' market-shares

At this stage, it is possible to compute the market shares predicted by the network model. They can be taken as estimations of the real market shares under two hypotheses: first, that shippers are actually minimizing their generalized transportation costs, a rather weak hypothesis; second, that the carriers' tariffs bear a close relationship with the operating costs presented in the above sections. This second hypothesis can largely be justified by the contestable character of each mode's market.

By simple additions, the results of the cost minimization provide us with a global modal split which can be compared with the observed modal split computed on the basis of the Eurostat data: 3% of transports by inland waterways, 7% for the railways, and 90% of transports by trucks.

It is also possible to compute the effects on the modal split of some cost variations. Here, we choose to vary the relative cost of road transports. To that effect, we implemented an iterative procedure that modifies, at each step, the relative operation costs of road transports, from 50% to 150% of the actual cost. As we progressed by steps of 10%, 11 iterations were needed for 11 successive assignments of the O-D matrix. At the end of each iteration, the relative market shares for the different transportation modes were computed. They are given in the following Table 1.

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5 If we had the appropriate information, we could have introduced at some points of the network an additional transit operation with the cost of congestion at that point. Note that it is possible to use with Nodus an algorithm which would compute an equilibrium solution spreading a given flow between several routes, if transport costs are made a function of the total traffic on a link.

6 Market shares computed for transports of more than 50 km.
<table>
<thead>
<tr>
<th>Wood</th>
<th>Relative Market Shares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Operation Costs for Road Transport (1 = 100%)</td>
<td>Road</td>
</tr>
<tr>
<td>0.5</td>
<td>95.63</td>
</tr>
<tr>
<td>0.6</td>
<td>95.48</td>
</tr>
<tr>
<td>0.7</td>
<td>95.03</td>
</tr>
<tr>
<td>0.8</td>
<td>93.72</td>
</tr>
<tr>
<td>0.9</td>
<td>91.6</td>
</tr>
<tr>
<td>1</td>
<td>89.6</td>
</tr>
<tr>
<td>1.1</td>
<td>87.88</td>
</tr>
<tr>
<td>1.2</td>
<td>86.43</td>
</tr>
<tr>
<td>1.3</td>
<td>84.33</td>
</tr>
<tr>
<td>1.4</td>
<td>82.99</td>
</tr>
<tr>
<td>1.5</td>
<td>81.6</td>
</tr>
</tbody>
</table>

Table 1

We can see that the market shares estimated by the network model at the actual cost level are very close to the observed market shares recorded by the Eurostat statistics. This suggests a rather good fit of the network cost model, and gives some support for its use in the present context. All the values corresponding to the various levels of the road relative cost have been plotted in the following diagrams. Note that in figure 4, the dotted curve corresponds to railways, while the continuous one corresponds to road transports.
These curves show the impact of a cost variation of road transport on the market shares for the different modes. If we accept the two hypotheses that shippers are minimizing their transports costs and that the three modes' markets are contestable, these curves can be assimilated to demand functions for the different modes.

In any case, they show that railways transports are much more sensitive to a cost variation of road transport than inland waterways transports. Clearly, this phenomenon is partly the result of the characteristics of the networks. Indeed, the flows were assigned on the whole European network, but the hydraulic network is only widely developed in the Benelux countries, the northern part of France and Germany. Hence, in the other countries, the only competitors of road transportation are often the railway companies, and the market share for inland waterway transportation in Europe could never increase very much.

The values given by Table 1 can also be used to compute direct and cross-elasticities with respect to cost. Table 2 presents these arc-elasticities for a 10% decrease in relative cost of road transport. Naturally, the « demand » for road transports appears to be inelastic with regard to its cost. On the other hand, the « demands » for the other modes, and particularly for railways are rather elastic with respect to the same road costs.

These results indicate that railways could substantially increase their share of the European transports market, if the costs of road transports were to increase, provided, naturally, that they have the capacity to do so.

<table>
<thead>
<tr>
<th>Elasticity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road (direct)</td>
<td>-0.21</td>
</tr>
<tr>
<td>Waterways (cross)</td>
<td>1.15</td>
</tr>
<tr>
<td>Railways (cross)</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 2
4. Concluding comments

As an illustration of the use of our network model, Section 3 has presented a very global analysis of the competitive positions of the three inland modes of transportation: rail, road, and waterways. Obviously, it is only the first step of an analysis which should examine separately and in more details different transportation corridors characterized by different competitive situations. For instance, a specific analysis should be made of the corridor between the North Sea harbors and Germany, where waterways can compete for some goods with road and rail transportation. The conditions of competition via the various types of transports between the Baltic and the North Sea harbors should also deserve a particular analysis, like the problem of the Alpine crossing routes, the links between the Scandinavian countries and Continental Europe, ...etc. Combined transports, containers, roll-on roll-off and piggy back transports on some routes should also require specific analyses.

All these problems could be the object of simulations with this network model, provided that, in some cases, more detailed data be available. This is because the virtual network is based on an exhaustive representation of all the transports movements and operations on the multimodal network. Hence, it is possible to vary any parameter of the cost functions attached to the virtual links. Detailed and comprehensive sensitivity or scenario analyses, such as used in evaluations of transport new infrastructure and policies, are thus made much easier.

5. Appendix: Specific cost functions

5.1. Cost functions for inland waterways

5.1.1. Boats:

Given: F, the annual fixed cost of the boat (constant annuity, insurance, maintenance and wages),
L, the for loading or unloading the boat,
u, the amount of working hours/year,
T, the average load of the boat in tons,
n, the number of workers for loading/unloading the boat,

\[ A = \frac{F \cdot L}{n \cdot u \cdot T} \]

Given: b, the fuel consumption per hour, 
\( \phi \), the average speed,

\[ B = \frac{F + b \cdot u}{u \cdot \phi \cdot T} \]

5.1.2. Barges

Given: \( F_p \), the fixed costs of the boat, 
\( F_b \), the fixed cost of the barges, 
t, the time needed to tie the barges,

we obtain \( A = \frac{F_p \cdot t + F_b \cdot L}{n \cdot u \cdot T} \), and \( B = \frac{F_p + F_b + b \cdot u}{u \cdot T \cdot \phi} \).

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7 Most of the data are based on the information provided by De Saint Martin (1989).
5.2. Trucks

For the trucks, the fixed costs do not include the maintenance which is included in the variable costs.
Given: $e$, the maintenance cost per km, 
c, the fuel consumption per km, 
\[
A = \frac{F^*L}{u^*T}, \quad \text{and} \quad B = \frac{F + (c+e)u^*\phi}{T^*u^*\phi}
\]

5.3. Trains

We have to separate the fixed costs for the locomotive ($F_m$) and for the wagons ($F_w$):
$F_m$ includes a constant capital annuity, insurance cost and wages,
$F_w$ includes a constant annuity, insurance cost and maintenance.
\[
A = \frac{F_m + F_w + (h+c)u^*\phi}{T^*u^*\phi}, \quad \text{and} \quad B = \frac{F_m + F_w}{T^*u^*\phi}
\]

Bibliography

Abdelwahad W.M. et M.Sargious, (1990), Freight Rate Structure and Optimal Shipment size in Freight Transportation,, The Logistics and Transportation Review, 6, 271-292.
Crainic T.G., M. Florian and D. Larin (1993), STAN, New Developments, Centre de Recherche sur les transports, Université de Montréal, papier de recherche n° 942.
Gathon H-J (1991); La performance des chemins de fer européens : gestion et autonomie, Thèse de doctorat, Université de Liège.

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8 The data are based on "Conditions d'exploitation et prix de revient dans le transport routier de marchandises à longue distance", (1991), Direction des Transports Terrestres du Ministère de l'Equipement, des Transports et de l'Espace, France.
9 The data are based on the published statistics of the Belgian railway company (S.N.C.B.). As there exists an infinite number of engine-carriage combinations, we have defined a standard diesel train and a standard electric train. Note that the Belgian cost data have been adjusted for each national railway, in order to take account of their varying efficiency. These adjustments are based on the work of Gathon (1991). For more details see Jourquin (1995).


